a\PRTS

10/505195
DT09 Rec'd PCT/PTO 19 AUG 2004

METHOD FOR RE-GRINDING AND POLISHING FREE-FORM SURFACES, ESPECIALLY ROTATIONALLY SYMMETRICAL ASPHERICAL OPTICAL LENSES

[0001] The invention relates to a method for grinding and polishing of free-form surfaces, in particular of rotationally symmetric aspherical optical lenses.

[0002] In contrast to spherical lenses used in many cases up to now, these aspherical lenses have special optical properties theoretically presenting the physical optimum. In practice, this means that images realized using these aspherical lenses are considerably more luminous intense and focused. They avoid errors such as the spherical aberration. Something similar applies for the even more irregular surfaces which are here called free-form surfaces. They can assume conical, wavelike, cylindrical or other shapes. The potential fields of application are even larger for them.

[0003] Therefore, the imperative necessity exists to produce these surfaces cost-efficiently. This is impossible at present, as all methods in use rest on the skills of experienced operators and/or on the use of production automats which do only work with very small tools. The diameters of these tools are mostly only about a tenth as large as those of the workpieces. For this reason, the aspheres produced up to now by grinding and polishing are very expensive.

[0004] The present invention addresses these problem points. On one hand, the grinding and the polishing and here, particularly, the corresponding correction passes are no longer controlled manually, but by a method according to claim 1 and subsequent claims. On the other hand, the tools described in claim 23 and subsequent claims provide a considerably higher, but nonetheless exactly controllable and reproducible removal. The invention enables thus considerably lower production costs.

[0005] There have already been several attempts to solve this problem, among others by the method of the patent JP9066464. So far, however, without success. In the method disclosed in this print, the surface to be processed is arranged into areas. Afterwards, all these together are calculated in a linear system of equations. In practice, it is impossible to solve such a system of equations in combination with effective tools for the entire free-form surface. The example

described in aforesaid print does hints at this point by its extreme simplicity. The defect alluded to here is none in the word's sense, because only a nearly planar surface is processed. Thus, it is impossible to increase the accuracy of the surface with this method by accordant control of the tools.

[0006] Subject of the invention is to avoid these disadvantages.

[0007] This problem is solved by arranging the free-form surface (1 or 4) into areas (Fig. 1 and Fig. 2), for example according to the tool's size. Each of these areas then still contains a plurality of positions entering into the calculation and is solved individually with a separate linear system of equations. As the areas mutually influence each other resulting from the width of the processing tool, their interaction must be taken into account. For this purpose, a zeroth order approximation, which estimates this interaction, enters into the respective linear system of equations. This interaction is also shown by the tool (2) positioned on the surface (4) in the area B8, wherein the tool is although processing and therefore influencing B7.

[0008] Furthermore, all of the workpiece's and tool's specifics such as the speed of rotation are taken into account. The plurality of solution sets resulting from the plurality of systems of equations are combined again and used for the controlling of the tool during the grinding or polishing.

[0009] Depending on the required accuracy of the surface and the existing errors in comparison to the diameter of the employed tool, different sizes of the areas are reasonable. As a result of the areas' interaction among each other depending on the tools' width, it is reasonable for the areas to have the same width or the double width of the tool (see also Fig. 2).

[0010] By the control of the influencing factors determining the grinding and the polishing, there is the possibility to control the removal on the surface by the dwell time and/or by the speed of rotation and/or by the contact pressure of the tool and/or by the speed of rotation of the workpiece.

[0011] By use of the method it becomes possible to remove just as much material from the surface that the specified surface emerges such that the lowermost point of the uncorrected (actual) surface (Fig. 5 minima of the curve 7), as this one has nearly not been processed, is still part of the generated specified surface. Practically, there has been removed as few material as possible, but nonetheless the specified shape has been realized. The minimal necessary removal has been realized. This is an decisive aspect for reducing the processing time. Up to now, it is mostly polished as long until some time the least accuracy is fulfilled. This leads to the consequence that rather as much material as shown in Fig. 6 curve 13 is removed and thus the processing is extended needlessly.

[0012] Contrary to arbitrary free-form surfaces, rotationally symmetric free-form surfaces exhibit a regularity in form of their rotational symmetry. It is negligible how the lens is skewed around its symmetry axis, the cross section of the surface's shape, as for example in Fig. 4 surface (1), is invariant. If these surfaces are processed by methods which exploit the rotational symmetry (see also Fig. 4), the errors of the surface are distributed rotationally symmetric, too. Then it is possible to carry out the control of the removal only radially. For the control of such a processing, the introduced method is transferred to an one-dimensional form. The virtual removal and the distribution of the areas is limited to the one-dimensional radial area (see Fig. 5). The processing is done under rotation of the tool and the workpiece then.

[0013] As no methods exist yet that enable the use of large tools and simultaneous increase the surface's accuracy or enhance it to a specified measure respectively, it has always been necessary to rework multiply and to remeasure repeatedly.

[0014] For the first time, this method enables simultaneously the use of large tools with simultaneous increase of the surface's accuracy in one pass of processing. Both aspects in combination with the control of all entities influencing the processing reduce production time to ten or less minutes (compare also the example on the preferred embodiment on this).

[0015] Partly, very high demands are made for the accuracy of surfaces. Nevertheless, the production costs shall be kept low. Up to now, this is impossible. Even in case of comparatively

large and wide errors, small tools are used, whereby very long production times result. Additionally, the surface is repeatedly measured between the processing passes with use of both equal and different, exchanged tools. Because of the clamping and unclamping and the necessary measuring time this requires a great effort which enhances the production costs greatly.

[0016] By the tool-specific use of the virtual removal of this method, the result of a first processing with a larger tool is already known even without remeasurement (see Fig. 7 curve 10). Based on this, a control for the subsequent processing with the smaller tool can be calculated for a further increase of the accuracy on base of the same method applying a different virtual removal specific for this smaller tool. The overall processing is considerably shorter than if the last used, smaller tool would have been used from the beginning. The saving of the remeasurement enables further reductions of costs.

[0017] To increase the fields of application of the method, overlapping areas are permitted in addition to non-overlapping areas. The areas B1, B2, B3 ... B9 shown in Fig. 10 overlap pairwise to 50%. For example, B3 overlaps to a half with B4 and in turn this one overlaps to a half with B5. There exist respectively 16 common mesh points or calculation points respectively.

[0018] An extension of the areas' overlap up to the extreme, where adjacent areas differ from each other in one value only, yields so much the better controls for the correction of the surface. For the example in Fig. 10, up to 132 areas (B1, B2, ..., B132) would result as a consequence.

[0019] Regarding the areas' overlap, the corresponding statement is also valid in the two-dimensional case. The number of areas increases quadratically here as the overlap of the areas is possible in two dimensions.

[0020] With this method, it is possible for the first time to produce aspheric glass lenses by grinding and polishing within 20 minutes.

[0021] In particular, concave lenses pose high demands to the control during the processing. Using this method, it is possible for the first time to produce concave lenses with a best-fit radius

of curvature of less than 50 mm within 40 minutes by grinding and polishing with a pv-accuracy of less than 600 nm.

[0022] For the decisive reduction of the processing times, this method enables the use of tools (2) with diameters of an eighth to a quarter of the diameter of the workpiece (Fig. 11) and is although able to correct the surface (1) (see also in the example on the preferred embodiment). In comparison to hitherto tools with a size of about a tenth, a more than six times larger removal and an corresponding shortening of the processing time becomes possible alone by the use of these tools.

[0023] Determining for the use of tools are the existing errors (7 in Fig. 12), which must be removed to reach the required accuracy. It is generally known that the tools used for the correction may only be as wide as the narrowest error, here 20 mm, which must be removed. With this method, it is possible to use tools which are twice as wide as the errors to be corrected or have the double diameter of 40 mm respectively. The errors are corrected as hitherto, however within a fourth of the time, because the processing surface is four times as large with the tool being twice as wide in comparison to the hitherto tool.

[0024] To ensure a constant removal over the time, the processing conditions have to be invariant. Therefore, the polishing or grinding foil (14 from Fig. 13), which is the material which gets in contact with the processing surface shall exhibit a homogenous structure which is free from bubbles, cracks or similar things. Additionally, the composition of the material itself shall be macroscopically even.

[0025] To be although able to ensure an even supply of polishing agent or cooling agent, perpendicular edges 15 (Fig. 13), through which the polishing agent or cooling agent can take effect approximately evenly below the entire surface of the tool, are inserted in this homogenous material of the polishing pad or of the grinding pad.

[0026] To further increase the speed of processing, it is necessary to enlarge the area of removal. However, an enlargement of the tools is not possible, as the necessary accuracy can not be reached anymore then.

[0027] This problem is bypassed by using several tools (2) simultaneously on the free-form surface (1 or 4) for the processing (Fig. 14 and 15). The reachable accuracy is just as high as when using only one tool of this size.

[0028] A reproducible removal is achieved here essentially, if the tools overlie the surface perpendicularly. Fig. 16 clarifies an arrangement of several tools which are all overlying the surface tangentially.

[0029] In the processing of rotationally symmetric free-form surfaces, the movement of each of the tools according to the method described above is advantageous.

[0030] If especially many tools shall process the surface simultaneously, it is advantageous if the movement of the tools is carried out along non-radial lines.

[0031] If the tools are particularly arranged then a processing of the surface is also then possible and reasonable if the tools do not move.

[0032] In this case, it has to be aimed for that in case of a rotating free-form surface the tools are arranged in such a way that the entire free-form surface is processed which is the case in the example from Fig. 14.

[0033] Solely by an arrangement of several tools it is possible to process free-form surfaces being neither spherical nor planar with more than five percent simultaneously processed area of the entire free-form surface, in a way such that the process remains controllable and keeps its correcting character.

[0034] The use of several tools is improved by separately controlling each of the single tools.

[0035] In case of using many tools, it is simpler, particularly if the handling system of the tools shall be universal for several lenses, if each of the tools exhibits a movable foot which ensures the condition that the tool overlies the free-form surface tangentially even in the case of a not fully correct arrangement.

[0036] The control of several tools on one free-form surface (1 or 4) is technologically very demanding, particularly on small surfaces. If several tools (2) are combined in mechanical compounds, a control of the removal is still possible with reduced fine mechanical complexity in a still sufficient amount.

[0037] The single tools may be combined mechanically in a rod-shaped compound (18) as can be seen in Fig. 18.

[0038] Besides, round compounds (17) are a possibility to combine single tools (2). They are advantageous in the sense of tangential overlying the tools especially on a round rotationally symmetric free-form surface (1).

[0039] Said compounds are controlled as single tools with a method according to claim 1 and subsequent claims by taking into account the different removal. The virtual removal must be adapted correpsondingly.

Example of an embodiment:

[0040] The example concerns an aspherical optical lens which shall be polished correctively. For this purpose, the lens is measured interferometrically. The error distribution measured before the processing is shown by Fig. 3. As the preceding polishing has already taken place in a rotationally symmetric manner as can be seen very well in Fig. 3, the errors existing on the surface are distributed rotationally symmetric. While both the lens and the tool rotate, the tool moves on a radial path while being aligned perpendicularly to the surface, from the edge of the

lens to the lens's center (Fig. 4). The correction of the errors shall be controlled along this way by means of the dwell time.

[0041] The total error consideration for the correction of this lens, in contrast to general free-form surfaces, is limited to the radial line. For the purpose of a simplified demonstration, a somewhat clear example is chosen here. The application of the method to general free-form surfaces means merely a transformation to two dimensions, thus the usage of an area instead of a (radial) line only.

[0042] The error of the entire measured surface is first averaged to the radial intersection. The result is shown by Fig. 5 in curve 7. The inside lying 0, the beginning of the axis of abscissae, denotes the lens's center, the end lying on the right denotes the lens's edge. Only the error of the surface with a peak to valley (pv) of about 1700 nm is depicted. In this example the whole method works with 130 mesh points, on which a calculation is carried out. For each point, the virtual removal is known. Based on this, one respective dwell time is created and used to control the removal during the processing. Each of these mesh points was created with measurement values from Fig. 3. These 130 mesh points correspond to a distance of 20 mm in this example.

[0043] The virtual removal of the tool is calculated for the entire surface on base of a foot print.

[0044] Now, the radial working line of 20 mm is divided into areas (Fig. 5). The tool possesses a width of 33 points, about 5 mm. The areas shall have the width of the tool. Thus, four areas B1, B2, B3, B4 result. For each of these areas, a system of equations is now build and solved, which contains the error of the surface in this area being lowered about the influence on the adjacent areas estimated by means of the zeroth approximation and the virtual removal at each of the 33 points belonging to the area.

[0045] As a result, the dwell times 11 depicted in Fig. 8 emerge. The dwell times at the respective 33 points, resulting from the four single systems of equations, have been put together here. These dwell times condition the forecasted removal which constitutes from the sum of the

curves 8 and 9 from Fig. 7. The resulting forecasted error distribution of the surface is shown by curve 10.

[0046] The processing of the surface with this control of dwell times took 5,48 minutes. The radially averaged distribution of the surface after the correction is shown by Fig. 9 in curve 12.

[0047] Between the mesh points 0 and 70 an accuracy better than 150 nm was achieved. From the point 70 to the edge of the lens, a pv-accuracy of pv 400 nm could be achieved. Thus, the forecasted error distribution corresponds to the error distribution actually arisen after the processing apart from small deviations in the absolute value.

[0048] The example shows that the method is able to correct difficult errors of a surface in extremely short time in the case of using large tools. An essential part of the shortening of the production time has, in addition to the large tool (diameter ratio tool : workpiece / 1 : 8), the ability of the method to remove exactly as much such that only the actually existing error is removed. With the methods uses hitherto, mostly much more removal was realized such that the processing took much more time. Fig. 6 shows a curve 13 which illustrates how much too much removal is removed in such cases. In this case, the processing time would increase to 20 minutes. Decisive is also that this result was reached in only one pass of processing without repeated remeasuring and reworking.

Description of the figures:

[0049] Fig. 1: Arrangement of a round free-form surface (1) into areas (3) in case of application of the tool (2) with diameter 16 mm (top view onto the free-form surface)

[0050] Fig. 2: Arrangement of a rectangular free-form surface (4) into areas (3) which are delimited by area boundaries (5) which correspond to the size of the tool (2) (top view into the free-form surface)

[0051] Fig. 3: Two-dimensional error distribution (6) of a rotationally symmetric optical lens (asphere)

[0052] Fig. 4: Motion-sequences in case of the processing of a rotationally symmetric optical lens (1) with a (polishing) tool (2) (side view / sectional view)

[0053] Fig. 5: Radial intersection of the error distribution (7) on the rotationally symmetric optical lens from Fig. 4; this corresponds to the minimally necessary removal

[0054] Fig. 6: Shifted radial intersection of the error distribution (13) on the rotationally symmetric optical lens from Fig. 4; this corresponds to the removal often realized hitherto

[0055] Fig. 7: Illustration of the method with actual state of the surface's error (7), the forecasted removal (sum from 8 and 9) and the forecasted remaining error after the processing

[0056] Fig. 8: The dwell times (11) determined by the method

[0057] Fig. 9: The remaining error (12) on the surface processed with these dwell times (11)

[0058] Fig. 10: Exemplary distribution of areas (B1, ..., B9) overlapping to 50 % within a radial intersection of a rotationally symmetric surface

[0059] Fig. 11: Proportions between tool and workpiece 1:8 and 1:4

[0060] Fig. 12: Comparison of size between the narrowest error of the error distribution () and the tool (2)

[0061] Fig. 13: Tool with adapted polishing or grinding foil (14) with perpendicular edges (15)

[0062] Fig. 14: Arrangement of several tools (2) on the round free-form surface (1)

[0063] Fig. 15: Arrangement of several tools (2) on the rectangular free-form surface (4)

[0064] Fig. 16: Arrangement of several tools (2) which overlie the free-form surface (1) tangentially, i.e. with perpendicular orientation

[0065] Fig. 17: Arrangement of round mechanical compounds (18) of tools (2) on a round free-form surface (1)

[0066] Fig. 18: Arrangement of rod-shaped mechanical compounds (18) of tools (2) on a rectangular free-form surface (4)

Numbers in the figures:

1 = Round free-form surface

2 = Tool

3 = Serially numbered areas (B1, B2, ...)

4 = Rectangular free-form surface

5 = Area boundaries

6 = Two-dimensional rotationally symmetric error distribution

7 = Radial intersection of the two-dimensional rotationally symmetric error distribution

8/9 = Forecasted removal

10 = Forecasted remaining error

11 = Determined dwell times

12 = Actually remaining error on the surface

13 = Too large error often removed hitherto

14 = Polishing or grinding foil consisting of homogenous material

15 = Perpendicular edges for supply of polishing agent or cooling agent

16 = Polishing or cooling agent

17 = Mechanical compound of tools of round type

18 = Mechanical compound of tools of rod-shaped type